Substellar Companions to Main Sequence Stars: No Brown Dwarf Desert at Wide Separations

John E. Gizis[1], J. Davy Kirkpatrick[1], Adam Burgasser[2], I. Neill Reid[3], David G. Monet[4], James Liebert[5] and John C. Wilson[6]

ABSTRACT

We use three field L and T dwarfs which were discovered to be wide companions to known stars by the Two Micron All-Sky Survey (2MASS) to derive a preliminary brown dwarf companion frequency. Observed L and T dwarfs indicate that brown dwarfs are not unusually rare as wide ($\Delta > 1000$ A.U.) systems to F-M0 main-sequence stars ($M > 0.5 M_\odot$, $M_V < 9.5$), even though they are rare at close separation ($\Delta < 3$ A.U.), the "brown dwarf desert." Stellar companions in these separation ranges are equally frequent, but brown dwarfs are $\gtrsim 10$ times as frequent for wide than close separations. A brown dwarf wide-companion frequency as low as the 0.5% seen in the brown dwarf desert is ruled out by currently-available observations.

Subject headings: binaries: general — stars: low-mass, brown dwarfs

1. Introduction

Understanding the processes, and distinctions between, star formation, binary formation and planetary formation is a major goal of stellar astronomy. A necessary step towards that goal is to understand the frequency of "brown dwarf" and "planetary" companions as a function of separation, primary mass, and secondary mass. It is now well-known that brown dwarfs are very rare as close companions to F-M dwarfs (the "brown dwarf desert," Marcy & Butler 2000) yet they are quite common in the field (Reid et al. 1999) and in open clusters (Bouvier et al. 1998; Martín et al. 1998).

[1]Infrared Processing and Analysis Center, 100-22, California Institute of Technology, Pasadena, CA 91125

[2]Department of Physics, 103-33, California Institute of Technology, Pasadena, CA 91125

[3]Department of Physics and Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA 19104-6396

[4]U.S. Naval Observatory, P.O. Box 1149, Flagstaff, AZ 86002

[5]Steward Observatory, University of Arizona, Tucson, AZ 85721

[6]Space Sciences Building, Cornell University, Ithaca, NY 14853

The purpose of this letter is to show that current data allow an estimate of the wide ($\Delta >$ 1000 A.U.) brown dwarf companion frequency to near-solar mass main sequence stars, despite the present lack of well-defined searches for wide companions. The observational constraints and resulting wide companion frequency are discussed in Section 2 and the differences between this fraction and the close companion frequency are discussed in Section 3.

2. Observational Constraints

2MASS searches for ultracool dwarfs are based on colors and magnitudes; although designed to find isolated field dwarfs, they are not biased against widely separated ($\gtrsim$ 40 arcsec) companions whose photometry is uncontaminated by the primary star. Three published brown dwarf companions with separations $\Delta > 1000$ A.U. have been identified in the course of 2MASS searches for isolated field brown dwarfs. The L4.5 dwarf Gl 417B has an estimated mass of $0.035 \pm 0.015 M_\odot$ and age $0.08 - 0.3$ Gyr while the L8 dwarf Gl 584C has a mass of $0.060 \pm 0.015 M_\odot$ and an age of 1.0-2.5 Gyr (Kirkpatrick et al. 2000, 2001). The T dwarf Gl 570D has a mass of $0.050 \pm 0.020 M_\odot$ and

an age of 2-10 Gyr (Burgasser et al. 2000). All are definitely substellar via spectroscopic crieria as well, since both L dwarfs pass the lithium test while the T dwarf is too cool to be a star. All three have been confirmed as companions by their common proper motion. These reflect the results from 2MASS searches of only a fraction of the sky — wide brown dwarf companions continued to be discovered. Wilson et al. (2001) will describe the discovery of three additional L dwarf secondaries at 880 A.U., 1090 A.U., and 2460 A.U.

The usual procedure for determining companion frequency is to survey a number (N) of potential primary stars. If n brown dwarfs with spectral type L are found, the frequency of L dwarf companions (in the searched separation range) is simply $f_L = \frac{n}{N}$. In the case of imaging surveys, only a fraction (y_L) of the brown dwarfs can be detected as L dwarfs, since brown dwarfs fade to very low temperatures and luminosities. Modelling of y_L allows an estimate of the true brown dwarf frequency to be $f_{bd} = \frac{n}{y_L N}$. In principle, the Two Micron All-Sky Survey (2MASS) allows a search for wide companions to nearby stars, allowing f_L and f_{bd} to be determined. A complete search, however, has not yet been made, due to the complexities of the task.

It is nevertheless possible to estimate the frequency of wide-separation brown dwarf companions, since the frequency can also be expressed as

$$f_{bd} = \frac{\rho_{comp}}{\rho_{star}} = \frac{\rho_{comp}}{\rho_{bd}}\frac{\rho_{bd}}{\rho_{star}} = \frac{g_w \rho_{bd}}{\rho_{star}} = \frac{g_w \rho_L}{y_L \rho_{star}}$$

In this equation, ρ_{star} is the space density of stars (the potential primaries), ρ_{comp} is the space density of wide brown dwarf companions, ρ_{bd} is the space density of field brown dwarfs found by 2MASS, and g_w is the frequency of field brown dwarfs that have a stellar primary at $\Delta > 1000$ A.U. Each of these variables can be estimated from published data. Separations of 1000 A.U. correspond to 40 arcseconds at 25 parsecs distance, and larger values at closer distances. For these wide systems, the presence of the main sequence star does not affect the identification of the brown dwarf in searches for isolated field objects. In the final step, we have assumed that g_w for all brown dwarfs is the same as g_w for L dwarfs. [7]

The observed space density of L dwarfs can be determined using the Kirkpatrick et al. (1999) sample of L dwarfs. Adopting the limiting magnitude $K_s = 14.7$ and the Kirkpatrick et al. (2000) spectral type-M_{K_s} relation, the Schmidt (1968) $\frac{1}{V_{max}}$ technique yields an L dwarf space density of $\rho_L = 0.0057 \pm 0.0025$ pc^{-3}. The space density of T dwarfs is highly uncertain but comparable (Burgasser et al. 1999). Only a small fraction (y_L) of brown dwarfs are observable as L, or even T, dwarfs. We can estimate y_L in two ways. *If* the mass function of companions is similar to that of isolated field brown dwarfs, then we can use the correction determined for isolated brown dwarfs. Reid et al. (1999) estimate that *if* the substellar mass function can be described as a power law $\frac{dN}{dM} \propto M^{-\alpha}$ extending down to $0.01 M_\odot$, then $\alpha \approx 1.3$ and $\rho_{bd} \approx 0.10$ b.d. pc^{-3} with large uncertainties. For the cases $\alpha = 0.0$, 0.6 and 1.0, then $\rho_{bd} \approx 0.02$, 0.04 and 0.07 b.d. pc^{-3} respectively. Surveys of the Pleiades are consistent with $\alpha \approx 0.6 - 1.0$ (Bouvier et al. 1998; Martín et al. 1998), and neither that cluster nor the field is consistent with $\alpha = 0$. We adopt $\rho_{bd} = 0.07 \pm 0.03$ b.d. pc^{-3}; hence, the ratio of L dwarfs to brown dwarfs is $y_L \approx 0.08$.

Alternatively, we may attempt to estimate the parameter y_L directly from the properties of the L dwarf companions. Gl 584C is just at the limits of detectability; since its age is in the range 1.0-2.5 Gyr, it is only detectable for 0.1-0.25 of the age of the disk. Gl 417B is easily detectable as an L4.5, but would have been detectable down to spectral type L8. Comparison to evolutionary tracks indicates it would then be visible to an age of 0.3-1.0 Gyr. The companions themselves then imply a correction factor y_L in the range 0.07 - 0.18 — consistent with the isolated brown dwarf estimate.

The fraction of the "isolated" field brown dwarfs which are actually wide companions to main sequence stars can be estimated from the 2MASS field brown dwarf searches. Over 100 field L dwarfs are now published, primarily from the 2MASS (Kirkpatrick et al. 1999, 2000), DENIS (Delfosse et al. 1999), and SDSS (Fan et al.

[7] Some of the field L dwarfs used in our calculation will not be brown dwarfs; however, since both Gl 417B and Gl 584C are confirmed brown dwarfs, accounting for this effect will only *increase* the derived brown dwarf companion frequency.

2000) surveys, of which two are wide companions to near-solar mass stars. Many of the L dwarfs, however, are at large distances (> 25 pc), where it would be difficult to discover an L dwarf companion due to proximity of the primary star. We choose to consider only L dwarfs within 25 parsecs because at this distance, we can be confident that bright (F-K) primaries are cataloged and the L dwarf companions at $\Delta > 1000$ A.U. will be detectable. In this case, 2 of 40 L dwarfs (Kirkpatrick et al. 2000, Table 4) have primaries, indicating the fraction of field L dwarfs which are actually wide companions is $g_w = 0.05 \pm 0.04$. This estimate is supported by the ongoing 2MASS T dwarf search (Burgasser et al. 1999), which has now discovered 17 field T dwarfs Burgasser (2000). Since T dwarfs are simply the older counterparts of L dwarfs, the fraction of 'field' dwarfs which are companions should be roughly the same. One (Gl 570D) of the T dwarfs is the fourth member of a K/M/M/T quadruple system (Burgasser et al. 2000), leading to an estimate of $g_w = 0.06 \pm 0.06$. (Note that Gl 229B is too close to Gl 229A to be counted or even detected by 2MASS.) Combining the L dwarf and T dwarf values, we adopt $g_w = 0.05 \pm 0.03$.

The space density of stars which are potential primaries for the brown dwarfs can be determined from the nearby star catalog as modified by Hipparcos parallaxes. All of the primaries to wide L/T dwarf companions (including the new Wilson et al. 2001 systems),have $M_V < 9.5$ (or Mass $> 0.5 M_\odot$). Jahreiß & Wielen (1997) find that the space density of stars with $M_V < 9.5$ is 0.020 ± 0.001 pc^{-3}. These are F to M0 main sequence stars. We do not consider fainter primaries because the incompleteness of the late-M dwarf catalog means that we might not recognize their presence near an L dwarf. We therefore have insufficient information to calculate the M/L dwarf binary statistics. [8] We can now estimate the wide brown dwarf companion frequency to main sequence stars. Taking the stars with $M_V < 9.5$ as the available primaries, we find $f_L = 0.014 \pm 0.011$. These, however, represent only a small fraction of the total brown dwarf population. We estimate $f_{bd} = 0.18 \pm 0.14$ by assuming a mass function $\alpha = 0.7$; the y_L values from the companions themselves suggest values in the range 0.08-0.20 ± 0.14.

The large uncertainties — due to the fact that the estimates are based only 3 companions — indicate that a larger survey is needed to determine the brown dwarf companion fraction; we certainly cannot prefer $f_{bd} = 0.18$ over $f_{bd} = 0.05$ given the uncertainties. However, it is important to realize that the error bars are non-Gaussian and that very low companion fractions (f_{bd}) are already ruled out with statistical significance. The situation is illustrated in Figure 1. We run Monte Carlo simulations of samples of 57 brown dwarfs and determine the percentage that have at least 3 wide companions. (For each value of f_{bd}, we run 200,000 simulations.) The solid line plots our preferred scenario: A brown dwarf space density of 0.07 pc^{-3} (equivalently, $y_L = 0.08$) and all primaries with $M_V < 9.5$ considered. It is possible to consider other scenarios. If $\rho_{bd} = 0.02$, equivalent to assuming $\alpha = 0$ or $y_L = 0.29$ (long-dashed line), then values of f_{bd} as low as 0.015 can still be excluded at the 95% confidence level. This corresponds to a scenario in which nearly all brown dwarfs are relatively massive and therefore detectable as L dwarfs for many Gyr; in this case, the observed L dwarfs represent a larger fraction of the total brown dwarf population. We finally consider an extreme model, in which $\rho_{bd} = 0.02$ and $\rho_{star} = 0.059$ pc^{-3}. In this case, the brown dwarf binary fraction can be much lower; in other words, we can reduce the reported brown dwarf fraction by averaging the many brown dwarf companions to $M > 0.5 M_\odot$ primaries with the more numerous population of lower mass stars for which no wide brown dwarf companions have ever been detected.

3. Discussion

The existence of the "brown dwarf desert" separating stars from "planets" at separations less than 3 A.U. is well established (Halbwachs et al. 2000). The review of Marcy & Butler (2000) finds that *less than* 0.5% of F-M dwarfs have brown dwarf companions down to $0.01 M_\odot$ on the basis of

[8]Note that the early-M dwarfs with $9.5 \le M_V < 13.5$ contribute another 0.039 ± 0.008 stars pc^{-3}, implying that we could decrease the derived brown dwarf frequency by a factor 2.9 — but in this case we face the puzzling fact that the chance of all 5 primaries having $M_V < 9.5$ is only $\sim 0.4\%$. An analogous difficulty in interpretation would occur if a search for companions amongst F-M dwarfs found companions only around the F, G and K dwarfs.

over 500 stars. The Mazeh et al. (1992) analysis of the 164 nearby G dwarfs studied by Duquennoy & Mayor (1991) indicates that $13 \pm 3\%$ of G dwarfs have *stellar* companions in this separation range, and that the mass distribution of these close companions is lacking in very-low-mass stars (a "red dwarf steppe"?) compared to both wider companions and the field mass function. On the basis of Duquennoy & Mayor (1991)'s analysis (their Figure 7), we estimate that 12 ± 3 % of G dwarfs have stellar companions with separation $\Delta > 1000$ A.U.

Our evidence that F-M0 dwarfs have a significant ($f_{bd} = 18 \pm 14\%$) population of very-low-mass companions at wide separations indicates that the orbital separation distribution of brown dwarf companions is not simply a scaled-down version of the stellar companion distribution. G dwarfs have approximately equal numbers of stellar-mass companions at separations $\Delta < 3$ A.U. and $\Delta > 1000$ A.U. ($r_{1000/3} \approx 0.9$); in contrast, we estimate their brown dwarf companions are at least four, and probably many more, times more common at the larger separations ($r_{1000/3} \gtrsim 4$). Within the very large uncertainties, the number ratio of stellar and brown dwarf companions may be near unity, similar to the ratio for isolated stars and brown dwarfs (Reid et al. 1999), although a considerably larger sample is needed to investigate this. The fact that all the primaries are relatively massive suggests that wide brown dwarf companions do not form around — or are not retained by — less massive ($M < 0.5 M_{\odot}$) primaries, although the incompleteness of the nearby star catalog for M dwarfs may contribute to this effect. The extreme limit to this is noted by Reid et al. (2001), who find that L dwarf primaries lack companions beyond ~ 10 A.U. Where the "brown dwarf desert" for F-M0 dwarf primaries ends is unclear at present, but searches around stars in the range 1-100 A.U. have generally had little success even though this range is the peak of stellar companion distribution for both G and M dwarf primaries (Duquennoy & Mayor 1991; Fischer & Marcy 1992). Most recently, Schroeder et al. (2000) failed to discover any brown dwarfs despite a sensitive *Hubble Space Telescope* search at separations of $1 - 60$ A.U. around 23 stars, while the extensive, highly sensitive search of 107 stars by Oppenheimer et al. (2001) found only 1 brown dwarf in range $40 - 120$ A.U. (Note that these volume-limited samples are dominated by M dwarf primaries with $M < 0.5 M_{\odot}$.) The fraction in the range 100-1000 A.U. cannot yet be constrained, but the recent discoveries of three L brown dwarf companions at those separations (Rebolo et al. 1998; Goldman et al. 1999; Gizis et al. 2001) suggest that they *may* be as common as wide companions and that 2MASS should detect many more.

While the uncertainty of our derived companion fraction is large, perspective on the brown dwarf desert may be gained by considering the numbers of stars and brown dwarfs within 25 parsecs. There are 1297 main sequence stars with $M_V < 9.5$ in this volume according to the Jahreiß & Wielen (1997) luminosity function. Radial velocity surveys indicate that they will have fewer than 6.5 brown dwarf companions within 3 A.U. In constrast, three wide-separation (two L, one T) brown dwarf companions are already known to such stars even though 1) only a small fraction of the sky has been searched, 2) T dwarfs are not detectable all the way to 25 parsecs, and 3) older/lower-mass brown dwarfs are undetectable. Our numbers suggest another $\sim 16 \pm 9$ wide L dwarf companions within 25 parsecs will be found, representing only the young, massive tip of the brown dwarf population.

Combined with the Reid et al. (2001) observation that 20% of L dwarfs have H.S.T. resolved (> 0.1 arcsec) brown dwarf companions within 10 A.U. but that wider companions are lacking, (see also Koerner et al. 1999), there is strong evidence that the frequency of brown dwarf companions is strongly dependent on both primary mass and orbital separation. There is a "brown dwarf desert" at < 3 (or $\lesssim 100$?) A.U. for F to mid-M main sequence primaries, and another desert for wide ($\gtrsim 20$ A.U.) brown dwarf doubles. This situation arises naturally in some theories of star formation (Boss 1986; Bate 2000).

4. Summary

We use the field L and T dwarfs which were discovered to be wide companions to known stars to derive a preliminary brown dwarf companion frequency. The observed L and T dwarfs indicate that brown dwarfs are not unusually rare as wide (> 1000 A.U.) systems, even though they are rare ($< 0.5\%$) at close (< 3 A.U.)separations. The

current data indicate that $\sim 1\%$ of $M_V < 9.5$ primaries have a wide L dwarf companion; the brown dwarf fraction should be substantially ($5 - 13$ times) higher. Stellar companions in these separation ranges are equally frequent.

Our estimates indicate that continued searches for wide brown dwarf companions should not be discouraged by the existence of the "brown dwarf desert" at close separations. There is now strong evidence — from both the wide companions examined in this work, and the close double brown dwarfs examined by Reid et al. (2001) — that the brown dwarf companion frequency is a strong function of both primary mass and separation. A search using 2MASS for both stellar and brown dwarf companions with separation $\Delta > 100$ A.U. will be quite rewarding. Furthermore, provided the older and lower-mass wide brown dwarf companions are not stripped in the Galactic disk, the majority of the brown dwarfs should be intrinsically cooler than Gl 570D, suggesting that a deep wide-field SIRTF search near G and K dwarfs is a promising avenue to extend our knowledge of brown dwarfs.

J.E.G. and J.D.K. acknowledge the support of the Jet Propulsion Laboratory, California Institute of Technology, which is operated under contract with NASA. This work was supported by NASA's Jet Propulsion Lab through contract number 961040NSF, a core science grant to the 2MASS science team. This publication makes use of data products from 2MASS, which is a joint project of the University of Massachusetts and IPAC/Caltech, funded by NASA and NSF.

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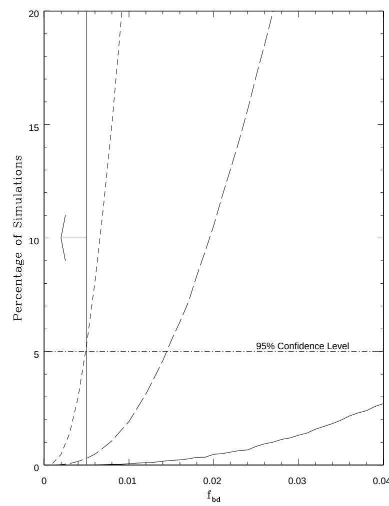

Fig. 1.— The percentage of samples in which 3 wide companions are found in a sample of 57 field brown dwarfs. The solid curve is our preferred model ($\rho_{bd} = 0.07$,$\rho_{star} = 0.020$); the long-dashed line is a model with few brown dwarfs ($\rho_{bd} = 0.02$,$\rho_{star} = 0.020$); the short-dashed curve is a model with few brown dwarfs and M dwarf primaries ($\rho_{bd} = 0.02$,$\rho_{star} = 0.059$). The position of the brown dwarf desert ($f_{bd} \leq 0.005$) and the 95% confidence level is also marked.